ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-THP027

# CRYOGENIC PERFORMANCE OF THE VERTICAL CRYOSTAT FOR QUALIFYING ESS SRF HIGH-BETA CAVITIES

S. Pattalwar*, A. J. May[1], K. Dumbell, P. A. Smith, S. Wilde, R. Buckley, P. Corlett, P. R. Davies, M. Ellis, S. Hitchen, P. Hornickel, M. Lowe, D. Mason, P. McIntosh, K. Middleman, A. Moss, A. Oates, M. D. Pendleton, P. Pizzol, T. Weston, A. Wheelhouse, J. Wilson
UKRI, STFC Daresbury Laboratory, Warrington, WA4 4AD, UK
[1]also at School of Physics and Astronomy, University of Manchester, Manchester, M13 9PL, UK

*Abstract*

An innovative vertical cryostat has been developed and commissioned at STFC Daresbury Laboratory for qualifying the high-$\beta$ SRF cavities for the ESS (European Spallation Source). The cryostat is designed to test 3 dressed cavities in horizontal configuration in one cold run at 2 K. The cavities are cooled to 2 K with superfluid liquid helium filled into individual helium jackets of the cavities. This reduces the liquid helium consumption by more than 70% in comparison with the conventional vertical tests. The paper describes the cryogenic system and its performance with detailed discussions on the initial results.

## INTRODUCTION

As part of the UK's in-kind contribution to ESS, STFC is responsible for the procurement, qualification, testing, and delivery to CEA Saclay of 84 high-$\beta$ Nb cavities. The high-$\beta$ cavities, which accelerate the beam from 628 MeV to 2500 MeV, are a five cell bulk Nb design operating at 704.42 MHz, designed at CEA Saclay.

2 K RF qualification of cavities with $Q = 5 \times 10^9$ will be required [1]. In order to support this activity, a novel Vertical Test Facility (VTF) has been designed and commissioned at the STFC Daresbury Laboratory.

## VTF CRYOSTAT DESIGN

The conventional method for VTF SRF cavity testing is to fully immerse the cavities in a large liquid helium (LHe) bath, and then pump the entire bath down to 2 K using a cold compressor/vacuum pump. RF testing is then carried out with the cavities at 2 K. This approach has been used successfully for many programs, including XFEL cavity testing at DESY [2]. Whilst well-proven, this technique requires both a large cryoplant and, for this activity, would require ~8500 L of LHe per testing run.

In light of the dwindling global supply of He, and associated rise in cost, an alternative cryostat architecture has been developed which requires significantly less LHe and a much smaller cryoplant throughput [3]. The cryostat is based on a cavity support insert (CSI) where three cavities are mounted horizontally inside LHe jackets below a header tank, each fed by a common fill/pumping line as shown in Fig. 1. By using this design approach, far less LHe is required per run (~1500 L) compared with the conventional design.

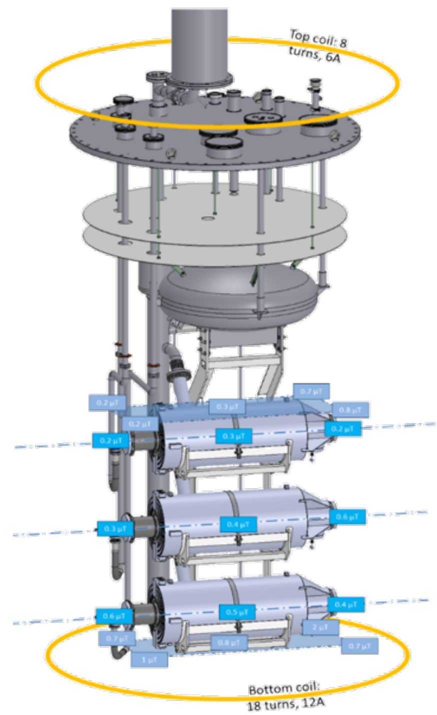


Figure 1: CSI with three dressed cavities installed.

The insert is mounted into a cryostat vessel which comprises the outer vacuum chamber, magnetic shielding (see below), and thermal radiation shields. The cryostat has been manufactured by Criotec[1] with the cooldown performances reported below.

An ALAT[2] Hélial 100 cryoplant, commissioned in 2018, supplies 50 K gaseous helium (GHe, produced by the first heat exchanger of the liquefier) and 4.2 K LHe. Sub-atmospheric pumps provide cooldown of the liquid to 2 K. The full system P&ID is shown in Fig. 2.

In total, 115 tests are anticipated; given the project timeline and a 2 week testing duration, this required the infrastructure and work flow to be developed for testing 3 cavities simultaneously. To facilitate this, two CSIs have been manufactured which can be used alternately in a single vacuum vessel. This will allow simultaneous testing of three cavities and preparation of the following three on the other insert, reducing down time between runs.

* shrikant.pattalwar@stfc.ac.uk

[1] criotec.com
[2] advancedtech.airliquide.com

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-THP027

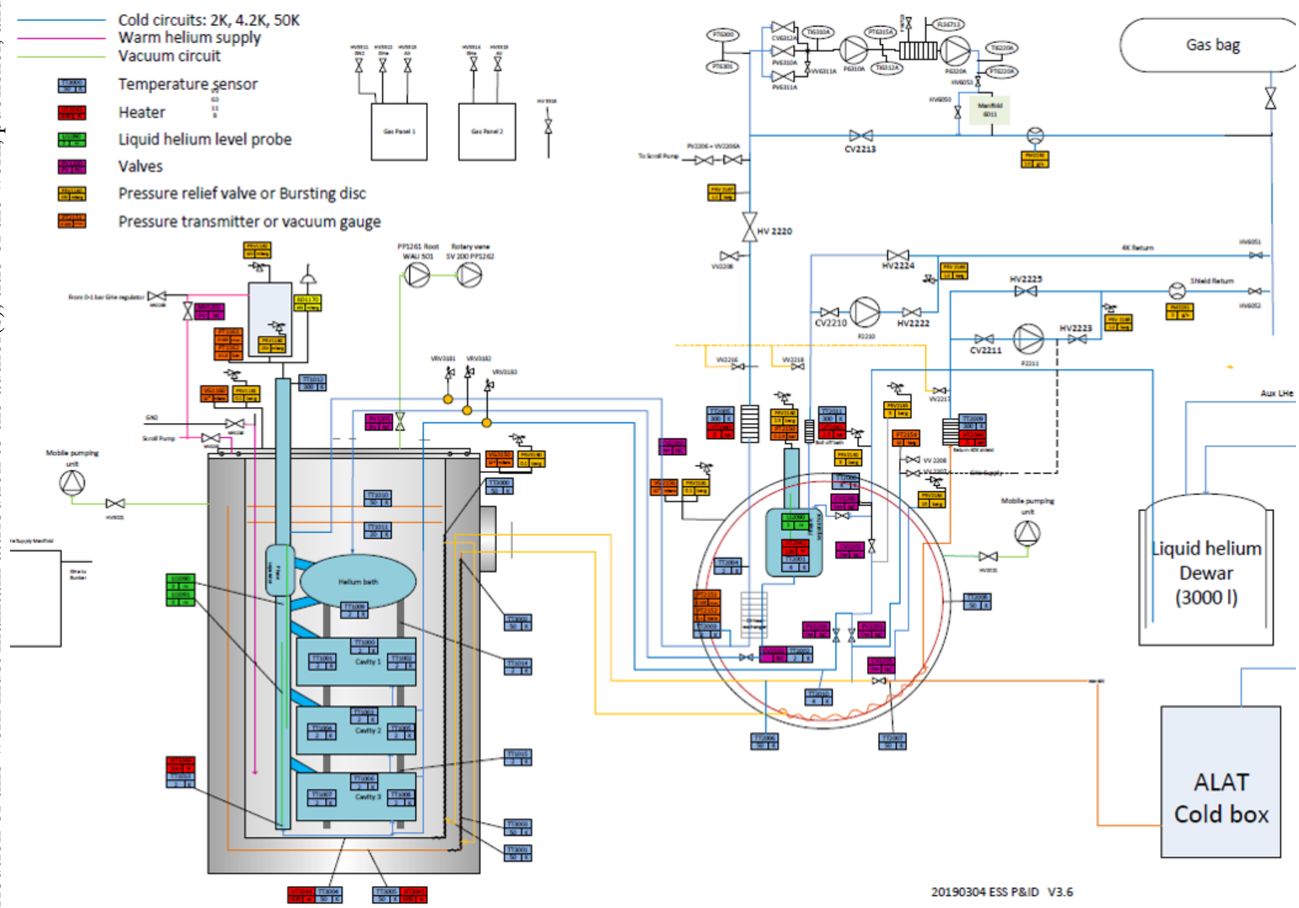

Figure 2: VTF P&ID with the cryostat shown on the left of the figure, the 2 K valve box shown in the centre, the 2 K pumps at the top, and the liquefier and cold box on the right.

## SAFETY

In the operation of any cryogenic facility, safety is paramount. Accordingly, significant efforts have been devoted to understanding potential failure modes for the facility as described above, and introducing mitigation strategies in consideration of the relevant regulations. A detailed treatment may be found in Ref. [4].

## MAGNETIC SHIELDING

Stray field attenuation at the cavities to <1.4 µT is achieved by a static Mu-metal magnetic shield[3] surrounding the cryostat.

Further attenuation to <1.0 µT is achieved through the use of two active coils located at the top and bottom of the cryostat as shown in Fig. 1. Coils are energised to ~6 A and ~10.8 A respectively to provide the desired attenuation.

## UHV SYSTEM

Two custom slow pump slow vent (SPSV) ultra-high vacuum (UHV) systems have been designed and manufactured for the CSIs. All components used for the build were processed for cleanliness and particle control before final assembly under ISO 4 cleanroom conditions. The first built SPSV system is presently installed on top of one of two CSIs, with the second to be installed in the coming months. SPSV systems are currently being testing using manual operation, although automation is planned for the near future.

Each SPSV system consists of three separate pumping lines that can operate at unbaked pressures down to $10^{-8}$ mbar. Mass flow controllers are used as variable valves that can control the flow of filtered $N_2$ gas into and out of the system, ensuring that the pressure does not change at a rate > 20 mbar/min and ensures that there is no particle migration within the system. As shown in Fig. 3, various separation and isolation valves allow for dynamic operation of the system as required. Residual gas analysers (RGAs) allow the partial pressures of residual gases to be measured within the system and loaded cavities. Each cavity must meet stringent vacuum acceptance criteria before the CSI is moved to the cryostat for cooldown. Fig. 4 illustrates a typical RGA scan for the system and was obtained as part of routine monitoring of a cold RF test of cavity P02 (see below) at 2 K.

[3] magneticshields.co.uk

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-THP027

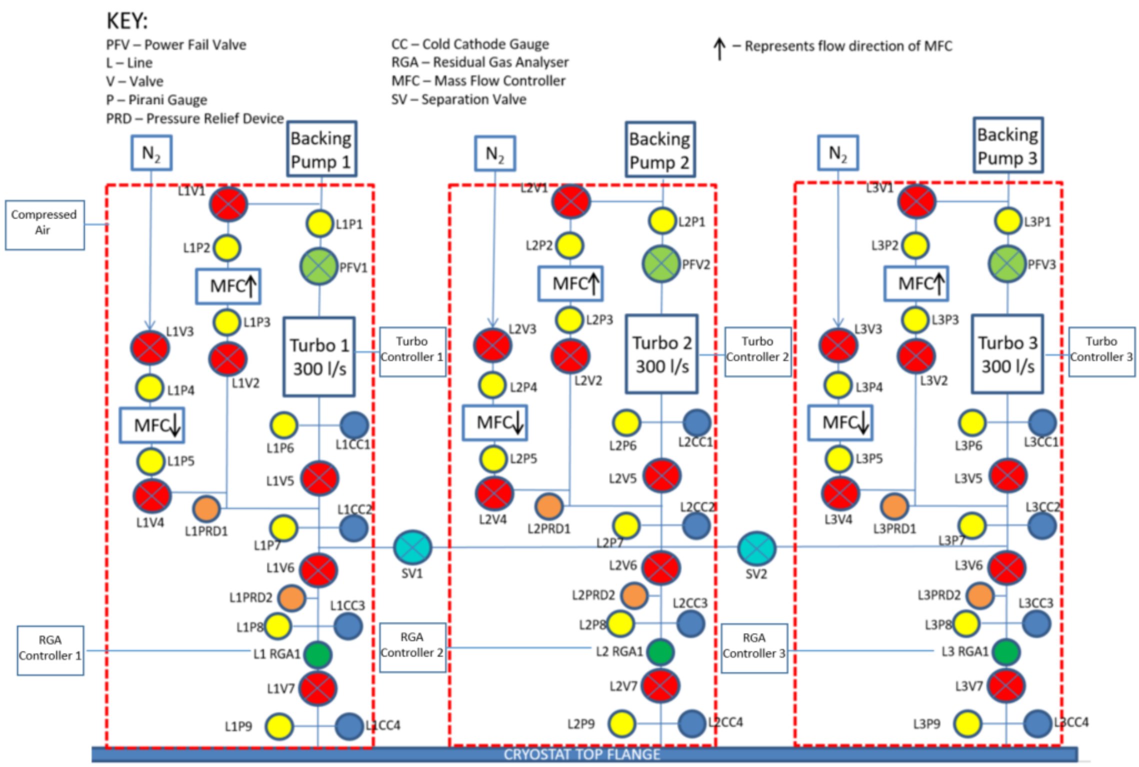


Figure 3: Schematic diagram of the SPSV system.

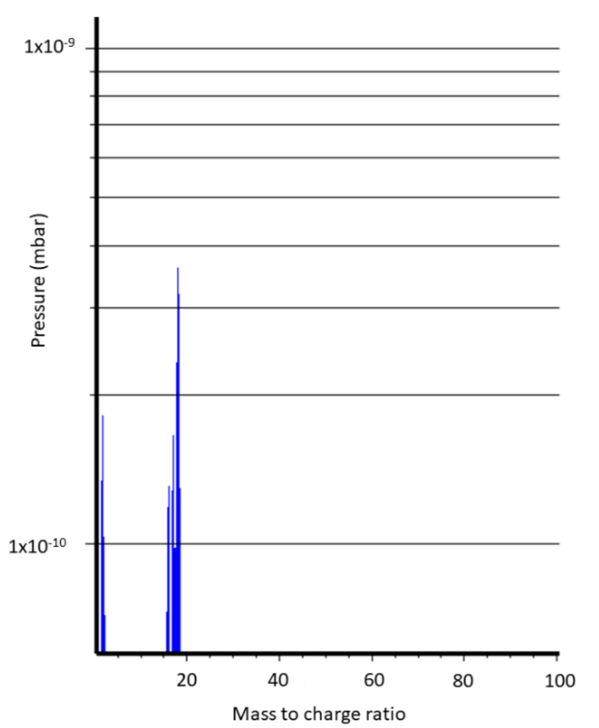


Figure 4: RGA spectrum taken during cold RF testing of cavity P02. Visible peaks correspond to H with mass to charge ratio of 2 and cracking pattern of $H_2O$ with mass to charge ratio ranging 16 to 18.

## CRYOGENIC PERFORMANCE

The first experimental run (Run-0) was carried out between October and November 2018 without any installed cavities in order to validate the base cryogenic operation of the system.

For the second experimental run (Run-1), which began in March 2019, a single prototype cavity (P02, provided by CEA Saclay) was installed in the middle cradle of the CSI.

After the dressed cavity was assembled on the CSI, the insert was mounted into the cryostat vessel. The vacuum space was evacuated and the lines to the cryoplant connected. A pump and purge procedure of the CSI circuit was then carried out with GHe at 300 K to minimise contamination and the possibility of ice blockages in the circuit during the subsequent cooldown. Shield cooling to 75 K was then carried out, taking ~36 hours as shown in Fig. 5.

LHe was then supplied to the CSI, completely immersing the cavities and filling the circuit (as shown in Fig. 2), cooling the cavities to 4.2 K. This duration of this phase was ~6 hours, as shown in Fig. 6.

The 2 K pumps were then used to reduce the temperature of the LHe bath and cavities down to 2 K. Excellent temperature and pressure stability was demonstrated at the level of ±1 mK and ±0.1 mbar respectively, as shown in Fig. 7.

Approximately half of the LHe inventory evaporates from self-cooling losses during this process. Whilst the system is designed to handle He mass flow of 4 g/s at 2 K, the measured mass flow is <2 g/s with the highest RF power applied to the cavities (see Fig. 8. This is significantly less

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-THP027



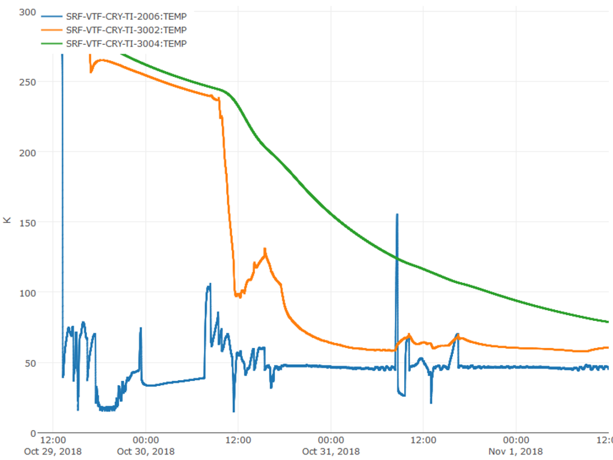


Figure 5: Shield cooldown to 50 K.

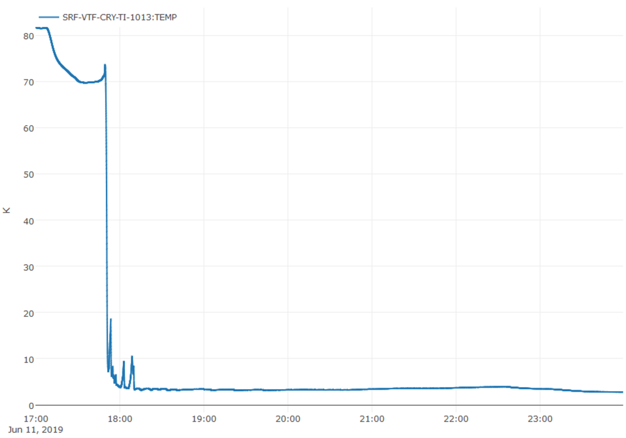


Figure 6: Cavity cooldown to 4 K.

than the ~20 g/s required by the conventional VTF approach, thus reducing the necessary size of the 2 K pumps, safety devices, valves and transfer lines.

In the absence of dynamic RF loading, the hold time of the system is sufficient so as to keep the cavities cold (liquid level >70%) for 18 hours between LHe top ups. In practice, LHe top ups have been carried out daily to support 2 K RF operations in Run-1, taking ~2.5 hours per fill.

At the end of Run-1, a fast warmup procedure will be used, as previously demonstrated in Run-0, where pumps will be used in a closed cycle to circulate GHe through the cold stages.

Using a 200 W heater on the 2 K stage, a series of experiments were conducted to simulate the cryogenic performance under the expected dynamic RF loading. A series of 40 s pulses up to 200 W were applied to the 2 K stage as shown in Fig. 8 along with the accompanying temperature rises.

## PRELIMINARY RF RESULTS

The main RF measurement and LabVIEW control system is taken from the design of T Powers from JLAB [5]. Modifications were made to achieve greater safety in operation, as well as to meet the requirements for the testing of the ESS

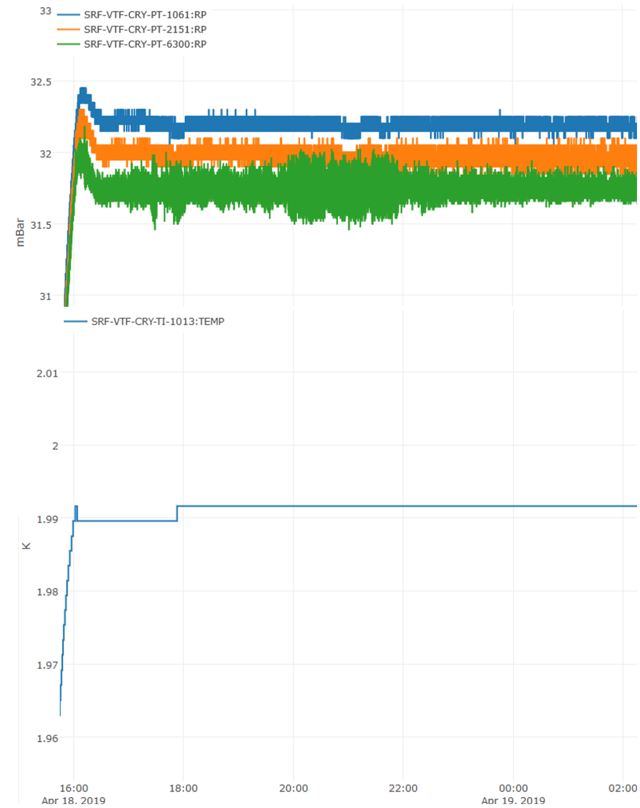


Figure 7: Pressure and temperature stability at 2 K.

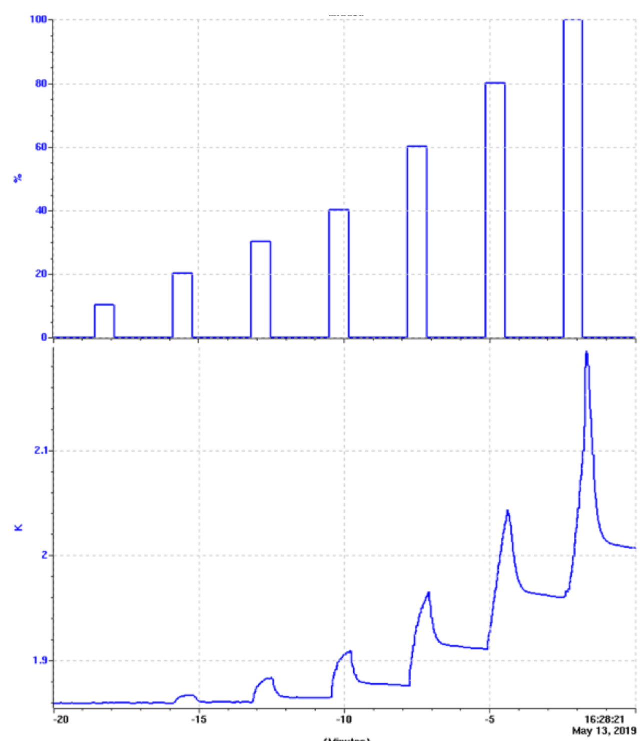


Figure 8: Measured 2 K stage temperature response to pulsed loading up to 200 W.

cavities. In order to validate the operation of the RF measurement system a Nb coaxial resonator was designed that

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-THP027

would fit inside a cryocooler [1, 6]. The $Q$ of the resonator was quite low, $\sim 5 \times 10^6$, as the temperature was on the order of 7.5 K. Measurements on the coaxial resonator were performed at a resonant frequency of approximately 712 MHz. Results are presented in Table 1 showing results derived from standard 3 db transmission measurements on a network analyser and the decay method.

Table 1: Coaxial Resonator $Q$ Measurements

| Measurement method | Loaded $Q$ | Unloaded $Q$ |
|---|---|---|
| Network analyser | $2.67 \times 10^6$ | $4.61 \times 10^6$ |
| Decay from LLRF in | $3.00 \times 10^6$ | $5.18 \times 10^6$ |

The ESS cavity specification states that the unloaded $Q$, $Q_u$, should be a minimum of $5 \times 10^9$ at an accelerating gradient of 19.9 MV/m. Preliminary results are shown below in Figs. 9 and 10 for relatively low power levels but these showed very good agreement with results from CEA Saclay. Typical error values were on the order of 10-15% which is consistent with standard measurement errors found by other authors [7]. Measurements were made in transmission using a very lightly coupled pick up probe ($Q_{ext} \sim 10^{11}$).

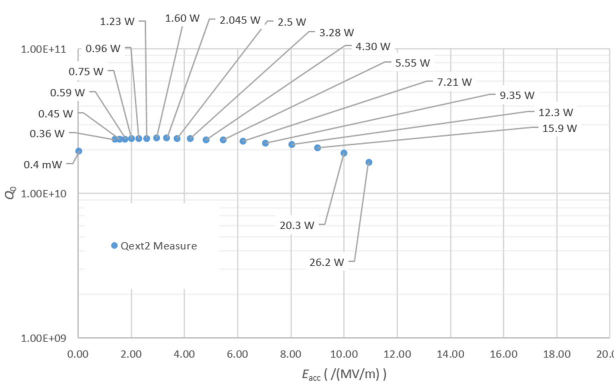


Figure 9: Measured $Q$ Against Accelerating Gradient for P02 at 2 K.

Measurements of $Q$ against temperature were made by allowing the temperature of the LHe bath to drift. Note the much smaller $\Delta T$ between the LHe and the cavity below the superfluid transition temperature at 2.2 K.

## CONCLUSION

A novel VTF facility for 2 K qualification of the ESS high-$\beta$ cavities has been developed and is being commissioned at STFC Daresbury Laboratory. Commissioning of the RF test equipment is well underway. Measurements made of the P02 test cavity are consistent with the data taken by CEA Saclay.

Both the design specification and measured performance in Runs 0 and 1 are consistent with the VTF facility operating on a 2-week cycle for testing the series production cavities. Alternating the CSIs will therefore allow testing

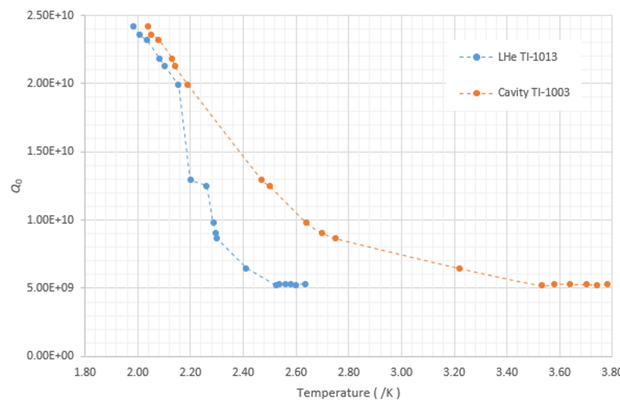


Figure 10: Measured $Q$ against temperature for P02.

of 6 cavities every 4 weeks, with the first series cavities arrivinge at Daresbury later this year.

## ACKNOWLEDGEMENTS

The authors would like to thank collaborators from ESS, CEA, and INFN, as well as industrial partners. They also would like to thank T Powers for his help in designing the test system as well as the use of the LabVIEW software from JLAB.

## REFERENCES

[1] P. A. Smith, L. Bizel-Bizellot, K. Dumbell *et al.*, "ESS High-beta Cavity Test Preparations at Daresbury Laboratory", in *Proc. SRF'17*, Lanzhou, China, Jul. 2017, pp. 137–140. doi:10.18429/JACoW-SRF2017-MOPB040

[2] J. Schaffran, D. Reschke, L. Steder *et al.*, "Analysis of the Test Rate for European XFEL Series Cavities", in *Proc. SRF'15*, Whistler, Canada, Sep. 2015, paper MOPB079, pp. 316–318.

[3] L. Bizel-Bizellot, M. Ellis, S. Pattalwar *et al.*, "Innovative Cryogenic Test Facility for Testing SRF Cavity Series Production", in *Proc. SRF'17*, Lanzhou, China, Jul. 2017, pp. 520–523. doi:10.18429/JACoW-SRF2017-TUPB060

[4] L. Bizel-Bizellot, S. Pattalwar, A. J. May *et al.*, "Cryogenic safety considerations for Vertical Test Facility for qualifying high-$\beta$ SRF cavities for the European Spallation Source", *In IOP Conference Series: Materials Science and Engineering*, vol. 502, no. 1, p. 012074, IOP Publishing, 2019.

[5] T. Powers and M. Morrone, "Jefferson Lab Vertical Test Area RF System Improvement", in *Proc. SRF'15*, Whistler, Canada, Sep. 2015, paper TUPB094, pp. 823–827.

[6] O. Malyshev, L. Bizel-Bizellot, K. Dumbell *et al.*, "Design, Assembly and Commissioning of a New Cryogenic Facility for Complex Superconducting Thin Film Testing", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 3859–3861. doi:10.18429/JACoW-IPAC2018-THPAL089

[7] T. Powers, "Theory and practice of cavity RF test systems", Thomas Jefferson National Accelerator Facility, Newport News, USA, No. JLAB-ACE-05-475; DOE/ER/40150-4011, 2006.